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DETECTABILITY OF STEP TRENDS IN THE RATE OF ATMOSPHERIC SULPHATE DEPOSITION

by

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ABSTRACT

Step trend analyses are performed on acid deposition rates using a combination of monitored sulphate deposition data and a long-range transport of acid precipitation (LRTAP) model. The step trend analyses considers Sudbury's emissions and eastern North America's emissions to explore strategies for reducing sulphur dioxide emissions such that a decrease in sulphate deposition is detected in a specified time period. Results indicate Sudbury's emissions could be reduced with significant detectable reductions in sulphate deposition occurring at the Muskoka region. Significant detectable reductions do not occur elsewhere due to the variability of monitoring data "masking" the small change in sulphate depositions associated with abatement. Reductions in eastern North America's emissions would result in widespread evidence of significant detectable reductions.

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INTRODUCTION

Acid rain is an important Canadian/American transboundary air pollution problem with detrimental effects observable over eastern North America. The problem has been acknowledged by both the Canadian and American governments as requiring remedial action and clean-up (e.g. Schiermeier and Misra, 1982). Mandates have been set to control emission levels, such as at Sudbury's smelting industries (INCO and Falconbridge Ltd.). However, there are still considerable needs for reduction in emissions before attainment of suggested depositon rates of 20 kg/ha are achieved at selected sensitive locations in eastern North America (Ontario Ministry of the Environment, 1980).

Decision-makers require information relating emission controls (or reductions) to the number of years of monitoring required to detect a significant change in sulphate deposition. A reduction of emissions does not simply imply reductions in sulphate deposition will be detected due to the introduction of wind and precipitation variability. If reductions occur, reductions in sulphate deposition may occur if wind and precipitation effects are minimal, i.e. average meteorological effects occur. However, if it should rain more in a specific year or wind effects occur such that a larger portion of sulphates are transported to a specific location, then sulphate depositions may be higher than in previous years, even with an emission reduction. As a result, a detectability of step trends analysis is required such that decision-makers may be able to report changes. Detectability of step

trends in the rate of atmospheric sulphate deposition represents the evaluation of the number of years of monitoring required to detect a significant change in sulphate deposition, given a specified reduction in sulphur dioxide (SO_2) emissions at various emission sources.

The major sources of SO_2 emissions in eastern North America are (i) coal-powered electricity generating stations, and (ii) industrial processes with the majority of SO_2 emissions coming from the smelting industry (Ontario Ministry of the Environment, 1980). The intensity of the emissions for 1980 are illustrated in Figure 1, from Barrie and Hales (1984) and have remained essentially constant throughout the early eighties. Canada has the largest point source of sulphur dioxide emission, consisting of INCO and Falconbridge Smelting Ltd., producing 944,000 tonnes of SO_2 per annum or 2.8% of the total North American sulphur dioxide emissions. Studies have been completed to characterize the effects of Sudbury's emissions on the wet and dry acid deposition on surrounding areas (Tang et al, 1984), but little work has been attempted in step trend analysis. Hirsch and Gilroy (1985) attempted a step trend analysis; however, they used an over-simplified model using precipitation as the only variable source of input into their model. They fit a relationship of precipitation data to wet sulphate deposition. However, wet sulphate deposition is calculated by multiplying concentration by precipitation. Therefore, their findings are debatable since precipitation and deposition are not independent.

Sulphur dioxide emissions result in the deposition of sulphur dioxides throughout eastern North America. Figure 2 from Barrie and Hales (1984) gives a spatial distribution of the sulphate deposition in eastern North America for 1980.

OBJECTIVES

Of concern, is the development of a methodology for detecting a step trend in the rate of atmospheric sulphate deposition. Existing sulphate deposition data are used to develop a relationship between changes in deposition levels and the number of years required to detect a significant change in the deposition level. The t-test is used to identify a significant change at the one-tailed 95% level of significance (LOS). This analysis is not to be confused with reducing deposition levels to suggested levels of 20 kg/ha/yr, but describe the ability to detect significantly reduced deposition levels (i.e. the step trend) after a reduction in emissions has occurred.

The above analyses require monitored sulphate deposition data for various selected locations or receptors to quantify statistics. Receptors must be selected based on the locations' sensitivity to acid rain. Data are accumulated for these locations and statistically analyzed for their validity in being able to spatially represent the location.

A model capable of simulating sulphate deposition data is required to relate percent emission reductions and the corresponding change in deposition levels. The annual UW-LRT model (Shipley et al, 1987) is used for this purpose. It has been revised into a seasonal model with the addition of precipitation variability, and calibrated and validated to existing monitored data (see Kompter and McBean, 1988 for details).

The final stage requires the combination of the above two analyses such that the resultant step trend is quantified as the percent emission levels to the number of years of monitoring required to detect a signficant reduction in sulphate deposition.

The foci of the step trend analysis is on:

1) the emissions from Sudbury's smelting companies, INCO and Falconbridge Ltd., and,

2) the entire eastern North American emissions network.

MONITORING DATA ANALYSES

The monitored data are obtained from sulphate deposition monitoring stations (Unified Deposition Data Base Committee, 1980 and 1984, Olsen and Slavich, 1986, and Barrie and Hales, 1984). Seven receptor locations are chosen based on their regional sensitivity to acid precipitation. Examining the monitored data for these locations, it is found that a large degree of variability exists between monitoring stations at any receptor location. Monitoring sulphate deposition data were aggregated for each receptor location, indicating the mean and variance of the sulphate deposition (listed in Table 1). This aggregation of the monitored data for each receptor location is denoted as an "airshed". Delineations of the airsheds are given in Figure 3. These airsheds and the basis for their delineation are discussed in Kompter, (1987).

The estimates of the statistics in the step trend analysis were calculated excluding the monitored data for the seasons of summer and fall of 1982 and winter 1983, since the emissions at Sudbury, during this time period were non-existent, and it is assumed that Sudbury is a major contributor to sulphate deposition. The resulting mean and standard deviations, are given as the first two columns in Table 2, along with n_1, the number of monitoring stations of data.

STEP TREND ANALYSIS

The monitored data were analyzed to relate the magnitude of sulphate deposition change, to the number of years of monitoring required to detect the change. The analysis was performed using the t-statistic (Iman and Conover, 1983), given as:

$$t_{0.95(1),n_1+n_2-2} = \frac{\bar{X}_1 - \bar{X}_2}{S_p\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \qquad (1)$$

where:

$t_{0.95(1),n_1+n_2-2}$ is the t-statistic at the one-tailed 95% level of significance (LOS) with n_1+n_2-2 degrees of freedom;

n_1 is the number of years of data (or data points before the change);

n_2 is the number of years to detect a change of magnitude $\bar{X}_1-\bar{X}_2$;

$\bar{X}_1-\bar{X}_2$ is the magnitude of change;

S_p^2 is the pooled variance given as:

$$S_p^2 = \frac{(n_1-1)^2 S_1 + (n_2-1)S_2^2}{n_1 + n_2 - 2} \qquad (2)$$

where:

S_1 is the standard deviation in the observed (monitored) data of n_1, and

S_2 is the standard deviation in the abatement data of n_2.

The standard deviation is assumed to be the same for S_1 and S_2, i.e. the variance is assumed to be the same before and after remediation. As a result, $S_1 = S_2 = S$ and rearranging the t-statistic, the magnitude of change, $(\bar{X}_1-\bar{X}_2)$ may be written as the following:

$$\bar{X}_1-\bar{X}_2 = t_{0.95(1)n_1+n_2-2} \quad S\sqrt{\frac{1}{n_1} + \frac{1}{n_2}} \qquad (3)$$

The magnitude of change $(\bar{X}_1-\bar{X}_2)$ from a reduced emission level to cause a significant reduction in deposition levels can be calculated given S, n_1, n_2 and using the corresponding t-statistic.

The calculations were performed using n_2 values of 1,2,3,4,5,10,25 and infinity (∞). Using the value of infinity for n_2 results in Equation 3 being reduced to:

$$X_1-X_2 = t_{0.95(1),\infty} \; S\sqrt{\frac{1}{n_1}} \qquad (4)$$

The resultant calculations of $\bar{X}_1-\bar{X}_2$ are given in Table 2. Muskoka will be used as an example to demonstrate how to read Table 2. From Table 2, to detect a significant change in deposition on an annual basis in one year of monitoring at Muskoka would require a change in deposition of 5.59 kg/ha. Monitoring over a two year period would require a reduction of 4.09 kg/ha on average to produce a significant reduction in sulphate deposition (at the one-tailed 95% L.O.S.). It may be noted that the required changes in deposition are large and arise because of the large variability from year to year and between monitoring stations.

LONG RANGE TRANSPORT OF ACID PRECIPITATION MODEL

The Long Range Transport of Acid Precipitation (LRTAP), Ontario Ministry of the Environment statistical model given in Shipley et al (1987) has been revised to simulate seasonal sulphate deposition data. Parameters used to revise the model are obtained from Venkatram et al, (1982), Ellenton et al (1985) and are used in the model described in Kompter and McBean (1988), which incorporates precipitation variability. Calibration and verification of this model (UW-LRT) is provided in Kompter and McBean (1988). Also, the revised model is capable of simulating at reduced emission levels. Sudbury's emissions are a significant contributor to sulphate deposition and during the seasons of summer and fall of 1982 and winter 1983, Sudbury's emissions were non-existent due to a shut-down. With these reduced emissions in the model, the model was capable of simulating the resultant sulphate deposition levels.

Model runs, for the step trend analysis were undertaken by setting the emission levels at percentages of 0% (i.e., no change), 25%, 50%, 75% and 100% (or reductions of 100%, 75%, 50%, 25%, and 0%, respectively). The changes in deposition $(\bar{X}_1-\bar{X}_2)$ are given in Table 3 for emission controls at Sudbury's smelters and Table 4 for emission controls across eastern North America.

COMBINING MONITORED DATA ANALYSES AND MODEL ANALYSES

Combining the relationships of Table 2 with Table 3 and Table 2 with Table 4, and eliminating $\bar{X}_1-\bar{X}_2$, results in percentage emissions as a function of n_2, as is indicated in Table 5 for Sudbury's emissions and Table 6 for eastern North America's emissions. As an example, consider Muskoka for a 75% emission level across eastern North America. A change of 5.0 kg/ha (from Table 4) will have occurred. Interpolating from Table 2, a change in deposition of 5.0 kg/ha would require more than one year but less than two years of monitoring to identify a statistcal reduction from the pre-abatement levels.

ANALYSIS OF SUDBURY AS AN EMISSION SOURCE

The results given in Table 5, indicate that the Muskoka airshed is the only airshed which would detect a significant reduction in sulphate deposition given the reduced emission levels at Sudbury. The remaining

airsheds would take an indefinite number of years to detect a change in deposition, i.e. Sudbury's emissions would not cause a significant reduction in sulphate deposition at the other airsheds. This indicates that statistically-significant detectable reductions in sulphate deposition would only occur near Sudbury, i.e. the Muskoka region. This becomes apparent when you consider the magnitudes due to the variance in the monitored data and compare them to the relatively small changes in deposition which occur due to the reduction of only Sudbury's emissions. The variability "masks" any reduction in sulphate deposition which may have occurred due to Sudbury's emissions.

ANALYSIS OF EASTERN NORTH AMERICA

A similar analysis to that performed on Sudbury's emission is performed using eastern North America's emissions. In other words, all of the emission sources in the model were computed at 0%, 25%, 50%, 65%, 75% and 100% emission levels. The results are given in Table 6, relating the percent emissions with the number of years to detect a significant difference (n_2).

As Table 6 indicates, if all of the sulphate emission sources in eastern North America were to reduce their emissions by 50%, it would take five years of monitoring (or less) to detect a significant change in acid deposition (at the 95% LOS), at all of the airsheds. At 65% sulphate emissions (or a reduction of 35%), it would take 12 years or less to detect a significant change in acid deposition at all of the airsheds. It should be noted that a 50% or 35% reduction of emissions does not indicate a 50% or 35% reduction at the airsheds because of the non-anthropogenic sources (quantified as background deposition). As an

example demonstration, 2/3 of Boundary Waters deposition and 1/2 of Algoma's deposition is due to background sulphate deposition; they require large reductions in emissions before detectable changes occur. In addition, the deposition at these two locations is below the suggested maximum deposition level of 20 kg/ha/yr. As a result, the major focus should be on the remaining five receptors.

CONCLUSIONS

The conclusions arising from this study include:

1) step trend analyses for acid precipitation require the combination of monitored statistical data and a model to relate the emission levels to the number of years of detection required to detect a significant reduction in sulphate deposition;
2) the step trend analysis of Sudbury's emissions abatement indicate that the Muskoka region would result in significant detectable reductions in sulphate deposition; however, decision-makers would not be able to detect significant reductions of sulphate deposition at the other selected airsheds;
3) the control of eastern North America's emissions indicate that a 50% reduction in emissions would require 5 years of monitoring or less to detect a significant reduction. For a 35% reduction, 12 years of monitoring or less would be required to detect a significant reduction in sulphate deposition;
4) Boundary Waters and Algoma require longer periods of monitoring to detect a significant reduction in sulphate deposition due to the large percentage of deposition due to background deposition, and,
5) the variability in the monitored data is large and tends to "mask" the size of the magnitude of change required to detect a

significant reduction in sulphate deposition. As a result, large reductions are required to detect any significant reductions.

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Table 1 Annual Monitored Data Summary Between Stations at an Airshed

		1980	1981	1982	1983	1984	Average
BW	$\bar{X}$	8.6	8.9	10.8	9.0	8.0	9.0
	s		2.2	1.0	1.8	1.4	1.0
	CV		0.25	0.09	0.20	0.18	0.11
	n	1	4	6	4	5	20
AL	$\bar{X}$	13.0	14.2	13.9	14.2	11.8	13.4
	s		4.5	4.9	4.0	2.1	1.0
	CV		0.32	0.35	0.28	0.18	0.07
	n	1	2	4	2	3	12
HU	$\bar{X}$	26.5	29.7	25.0	26.6	25.5	26.7
	s	0.8		1.4	3.3	3.1	1.8
	CV	0.03		0.06	0.12	0.12	0.07
	n	2	1	2	4	5	14
QC	$\bar{X}$	26.9	23.7	21.2		24.0	24.0
	x		6.9	0.1			2.3
	CV		0.29	0.00			0.10
	n	1	2	2		1	6
NH	$\bar{X}$	23.7	28.9	20.2	22.4	23.1	23.7
	s	3.2	9.1	0.1	1.2	5.7	3.2
	CV	0.14	0.31	0.00	0.05	0.25	0.14
	n	2	2	2	2	4	12
AD	$\bar{X}$	28.1	30.5	24.1	29.2	26.4	27.7
	s	3.8	6.7	4.0	5.5	7.8	2.5
	CV	0.14	0.22	0.17	0.19	0.30	0.09
	n	4	3	4	5	4	20
WP	$\bar{X}$	35.4	34.9	33.4	31.3	35.2	34.0
	s	4.!	5.1	3.4	4.6	5.2	1.7
	CV	0.12	0.15	0.10	0.15	0.15	0.05
	n	4	3	4	5	4	20

$\bar{X}$ - mean sulphate deposition (kg/ha)
s - standard deviation sulphate deposition (kg/ha)

CV - coefficient of variation ($s/\bar{X}$)
n - number of monitoring stations data for the airshed

Table 2 Changes in Average Annual Acid Deposition, Given Number of Years to Detect Change (n_2)

$\bar{X}$	s	n_1	n_2 1	n_2 2	n_2 3	n_2 4	n_2 5	n_2 10	n_2 25	n_2 ∞
BOUNDARY WATERS (BW)										
8.42	1.62	10	3.11	2.28	1.92	1.71	1.57	1.26	1.03	0.84
ALGOMA (AL)										
12.80	2.68	6	5.83	4.25	3.59	3.22	2.97	2.44	2.07	1.80
MUSKOKA (MU)										
26.26	2.78	8	5.59	4.09	3.45	3.09	2.85	2.30	1.92	1.62
QUEBEC CITY (QC)										
24.55	4.26	4	11.21	7.87	6.56	5.85	5.42	4.49	3.91	3.50
NEW HAMPSHIRE (NH)										
24.66	5.83	8	11.72	8.57	7.23	6.47	5.97	4.83	4.02	3.39
ADIRONDACKS (AD)										
28.13	5.85	11	11.08	8.08	6.79	6.05	5.56	4.42	3.58	2.90
WEST PENNSYLVANIA (WP)										
35.18	4.28	11	8.10	5.91	4.97	4.43	4.07	3.23	2.62	2.12

Table 3 Average Changes in Sulphate Deposition at Selected Sensitive Airsheds, Given the Percentage Emission Changes at Sudbury

	% Emissions				
	100%	75%	50%	25%	0%
Boundary Waters	0	0.03	0.06	0.09	0.12
Algoma	0	0.09	0.19	0.28	0.37
Muskoka	0	0.93	1.87	2.80	3.74
Quebec City	0	0.36	0.72	1.08	1.44
New Hampshire	0	0.26	0.52	0.78	1.04
Adirondacks	0	0.38	0.77	1.15	1.54
West Pennsylvania	0	0.25	0.51	0.77	1.02

Table 4 Average Changes in Sulphate Deposition at Selected Sensitive Airsheds, Given the Percentage Emission Changes in Eastern North America

	% Emissions					
	100%	75%	65%	50%	25%	0%
Boundary Waters	0.00	0.8	1.2	1.6	2.5	3.3
Algoma	0.00	1.8	2.6	3.7	5.5	7.4
Muskoka	0.00	5.0	7.0	10.0	15.0	20.0
Quebec City	0.00	4.2	5.8	8.3	12.5	16.7
New Hampshire	0.00	4.1	5.8	8.3	12.4	16.6
Adirondacks	0.00	5.5	7.7	11.0	16.6	22.1
West Pennsylvania	0.00	6.7	9.4	13.4	20.2	26.9

Table 5 The Number of Years of Monitoring Required to Detect a Significant Difference in Acid Deposition Based on Emission Reductions at Sudbury

	Emission Level				
	100%	75%	50%	25%	0%
Boundary Waters	∞	∞	∞	∞	∞
Algoma	∞	∞	∞	∞	∞
Muskoka	∞	∞	>25	<6	<3
Quebec City	∞	∞	∞	∞	∞
New Hampshire	∞	∞	∞	∞	∞
Adirondacks	∞	∞	∞	∞	∞
West Pennsylvania	∞	∞	∞	∞	∞

Table 6 The Number of Years of Monitoring Required to Detect A Significant Difference in Acid Deposition for Eastern North America

	Emission Level					
	100%	75%	65%	50%	25%	0%
	n_2	n_2	n_2	n_2	n_2	n_2
Boundary Waters	∞	∞	<12	<5	<2	<1
Algoma	∞	∞	<8	<3	<2	<1
Muskoka	∞	<2	<1			
Quebec City	∞	<13	<5	<2	<1	
New Hampshire	∞	<20	<6	<3	<1	
Adirondacks	∞	<6	<3	<2	<1	
West Pennsylvania	∞	<2	<1			

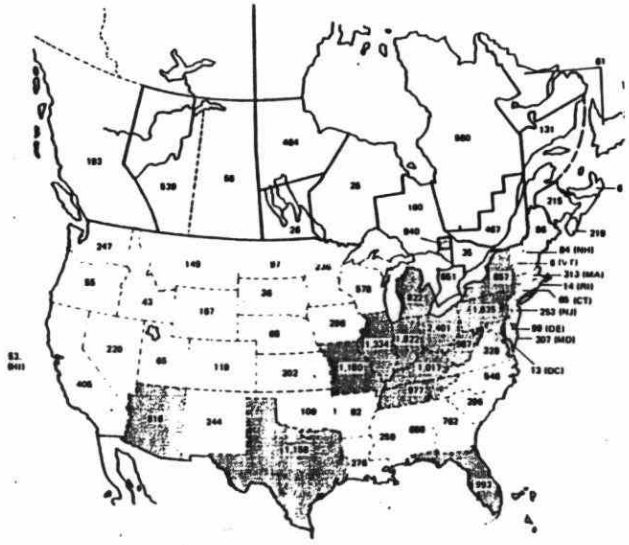

Figure 1 North American SO_2 Emissions in 10^3 Tonnes (1980) (Barrie and Hales, 1984)

Figure 2 Spatial Distribution of Sulphate (SO_4) Deposition in Eastern North America for 1980 (Barrie and Hales, 1984)

airsheds

o monitoring stations

1 Boundary Waters (BW)
2 Algoma (AL)
3 Muskoka (MU)
4 Quebec City (QC)
5 New Hampshire (NH)
6 Adirondacks (AD)
7 West Pennsylvania (WP)

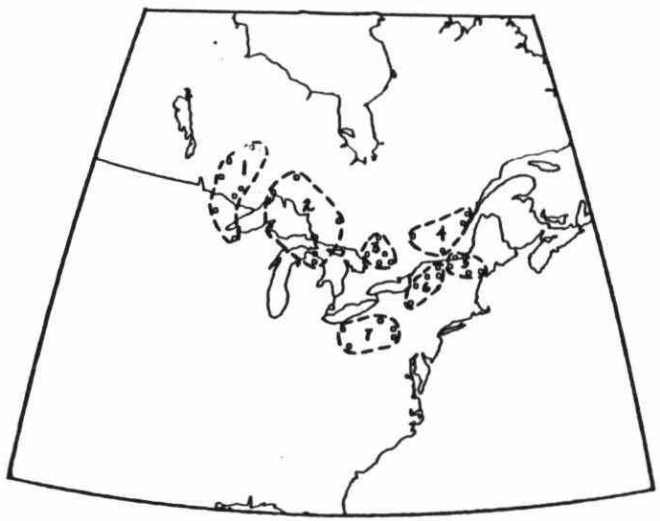

Figure 3 Airshed Locations With Monitoring Stations Within the Airshed Denoted